

D-branes and Deep Learning

Theoretical and Computational Aspects in String Theory

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Contents

Conformal Symmetry and Geometry of the Worksheet

Preliminary Concepts and Tools
D-branes Intersecting at Angles

Cosmological Backgrounds and Divergences

Deep Learning the Geometry of String Theory

Action Principle and Conformal Symmetry

Polyakov's Action

$$S_P[\gamma, X, \psi] = -\frac{1}{4\pi} \int_{-\infty}^{+\infty} d\tau \int_0^\ell d\sigma \sqrt{-\det \gamma} \gamma^{\alpha\beta} \left(\frac{2}{\alpha'} \partial_\alpha X^\mu \partial_\beta X^\nu + \psi^\mu \rho_\alpha \partial_\beta \psi^\nu \right) \eta_{\mu\nu}$$

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Symmetries:

- **Poincaré transf.** $X'^\mu = \Lambda^\mu_\nu X^\nu + c^\mu$
- **2D diff.** $\gamma'_{\alpha\beta} = (J^{-1})_{\alpha\beta}^{\lambda\rho} \gamma_{\lambda\rho}$
- **Weyl transf.** $\gamma'_{\alpha\beta} = e^{2\omega} \gamma_{\alpha\beta}$

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Conformal symmetry:

- **vanishing** stress-energy tensor: $\mathcal{T}_{\alpha\beta} = 0$
- **traceless** stress-energy tensor: $\text{tr } \mathcal{T} = 0$
- **conformal gauge** $\gamma_{\alpha\beta} = e^\Phi \eta_{\alpha\beta}$

Action Principle and Conformal Symmetry

Let $z = e^{\tau_E + i\sigma} \Rightarrow \bar{\partial}\mathcal{T}(z) = \partial\bar{\mathcal{T}}(\bar{z}) = 0$:

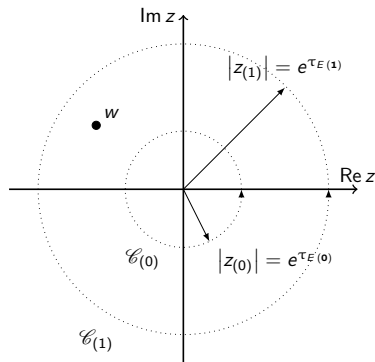
$$\mathcal{T}(z) \Phi_h(w) \stackrel{z \rightarrow w}{\sim} \frac{h}{(z-w)^2} \Phi_h(w) + \frac{1}{z-w} \partial_w \Phi_h(w)$$

$$\mathcal{T}(z) \mathcal{T}(w) \stackrel{z \rightarrow w}{\sim} \frac{\frac{c}{2}}{(z-w)^4} + \mathcal{O}((z-w)^{-2})$$

Virasoro algebra $\mathcal{V} \oplus \bar{\mathcal{V}}$

$$\left[\overset{(-)}{L}_n, \overset{(-)}{L}_m \right] = (n-m) \overset{(-)}{L}_{n+m} + \frac{c}{12} n(n^2-1) \delta_{n+m,0}$$

$$[L_n, \bar{L}_m] = 0$$



Action Principle and Conformal Symmetry

Superstrings in D dimensions:

$$\mathcal{T}(z) = -\frac{1}{\alpha'} \partial X(z) \cdot \partial X(z) - \frac{1}{2} \psi(z) \cdot \partial \psi(z) \quad \Rightarrow \quad c = \frac{3}{2}D$$

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$(\lambda, 0) / (1 - \lambda, 0)$ **Ghost System**

Introduce anti-commuting (b, c) and commuting (β, γ) conformal fields:

$$S_{\text{ghost}}[b, c, \beta, \gamma] = \frac{1}{2\pi} \iint dz d\bar{z} (b(z) \bar{\partial} c(z) + \beta(z) \bar{\partial} \gamma(z))$$

where $\lambda_b = 2$ and $\lambda_c = -1$, and $\lambda_\beta = \frac{3}{2}$ and $\lambda_\gamma = -\frac{1}{2}$.

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Consequence:

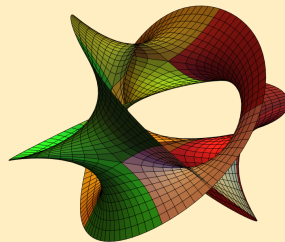
$$c_{\text{full}} = c + c_{\text{ghost}} = 0 \quad \Leftrightarrow \quad D = 10.$$

Extra Dimensions and Compactification

Compactification

$$\mathcal{M}^{1,9} = \mathcal{M}^{1,3} \otimes \mathcal{X}_6$$

- $\mathcal{X}_6$ is a **compact** manifold
- $N = 1$ **supersymmetry** is preserved in 4D
- algebra of $SU(3) \otimes SU(2) \otimes U(1)$ contained in arising **gauge group**

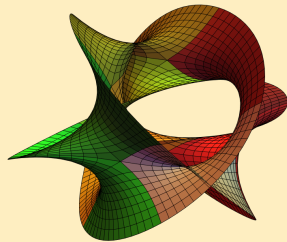


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Kähler manifolds (M, g) such that

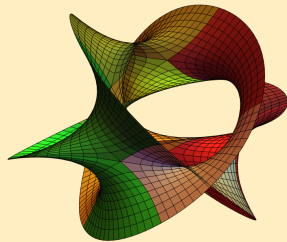
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Characterised by Hodge numbers

$$h^{r,s} = \dim_{\mathbb{C}} H_{\bar{\partial}}^{r,s}(M, \mathbb{C})$$

counting the no. of harmonic (r, s) -forms.

D-branes and Open Strings

Polyakov's action naturally introduces Neumann b.c.:

$$\partial_\sigma X(\tau, \sigma) \Big|_{\sigma=0}^{\sigma=\ell} = 0$$

satisfied by **open and closed** strings living in D dimensions s.t. $\square X = 0$.

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T-duality

$$X(z, \bar{z}) = X(z) + \bar{X}(\bar{z}) \quad \xrightarrow{T} \quad X(z) - \bar{X}(\bar{z}) = Y(z, \bar{z}) = Y(z) + \bar{Y}(\bar{z})$$

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Resulting effect (repeated $p \leq D - 1$ times) leads to **Dirichlet b.c.:**

$$\partial_\sigma X^i(\tau, \sigma) \Big|_{\sigma=0}^{\sigma=\ell} = 0 \quad \xrightarrow{T} \quad \partial_\tau Y^i(\tau, \sigma) \Big|_{\sigma=0}^{\sigma=\ell} = 0 \quad \forall i = 1, 2, \dots, p$$

thus **open strings** can be **constrained** to **$D(D - p - 1)$ -branes.**

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Introducing Dp -branes breaks $\text{ISO}(1, D - 1) \rightarrow \text{ISO}(1, p) \otimes \text{SO}(D - 1 - p)$.

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Massless Spectrum (*irrep* of little group $\text{SO}(D-2)$)

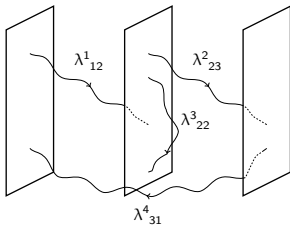
$$\mathcal{A}^\mu \leftrightarrow \alpha_{-1}^\mu |0\rangle \longrightarrow \begin{array}{ll} \mathcal{A}^A \leftrightarrow \alpha_{-1}^A |0\rangle, & A = 0, 1, \dots, p \\ \mathcal{A}^a \leftrightarrow \alpha_{-1}^a |0\rangle, & a = 1, 2, \dots, D-p-1 \end{array}$$

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Introducing **Chan-Paton factors** λ^r_{ij} , when branes are **coincident**:

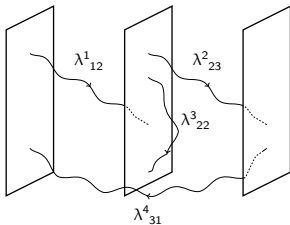
$$\bigoplus_{r=1}^N \text{U}_r(1) \longrightarrow \text{U}(N)$$

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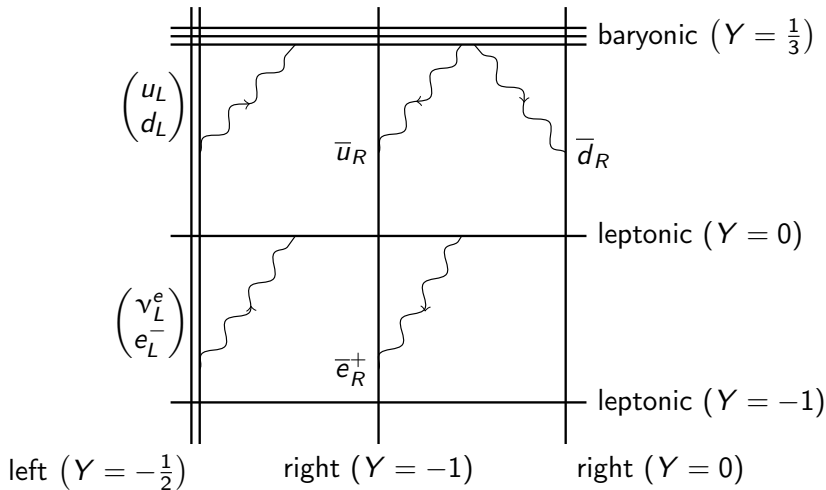


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Build gauge bosons, fermions and scalars.

Standard Model-like Scenarios



Intersecting D-branes

Consider N intersecting $D6$ -branes filling $\mathcal{M}^{1,3}$ and **embedded in** $\mathbb{R}^6$

Twist Fields Correlators

$$\left\langle \prod_{t=1}^N \sigma_{M_{(t)}}(x_{(t)}) \right\rangle$$

BBB

b

CCC

C